Optimization of the Foundation and Steel Structure of a Solar Panel Field.

Master´s thesis in Geoengeering, Aalto University

Research Partner

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Aalto-yliopisto

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BACKGROUND

- At present there is highly demand of Solar Energy in Nordic countries.
- Finland and Sweden most of areas with peat and weak soil land can be utlized for the Solar Panel area.
- Construction of Steel as foundation in Solar Panel in Soft soil (Clay areas) is challenging.
- SSAB is looking to find the use of Steel piles in Geotechnical challenging areas of Finland like peat and soft soils.
- Thus, the research will focus:
  - Optimized solution of proper use of Steel piles in soft soils. (Clay Areas).
  - Analyze the structural loading factor Solar Panel Frame. (Uplifting, Cyclic Loading, Normal Load)
  - To study the issue of corrosion and suggestion of solution for corrosion problem.

LITERATURE REVIEW ON NORDIC WEAK SOIL

PEAT AREAS

- Finland 1/3 land peat. (4-6 meter thick in southern Finland)
- Highly organic and moisture content i.e corrosive areas
- (Hollingshead and Raymond, 1972) Drained test result the value of Cohesive strength $c'=4$ kPa and Friction angle $\phi'=34°$.
- Most Vane test carried in Finland suggest that the undrained shear strength of peat is mostly between 10 and 15 kPa.
- In research Norwegians peat: common 3-4 meter thick, 2-8 kPa undrained shear strength
- If Peat is considered as cohesive soil, then shaft resistance will give ultimate resistance (small C.S.A in Piles)

CLAY AREAS

- In general Finnish clay undrained strength is between 5-15 kPa.
- Typical undrained shear strength was obtained from vane test (normally in Finland & Sweden)
- Cohesive piles are suitable for thick clayey soil.
- Settlement is high in clay area i.e should have high shaft resistance in pile designing.
- Corrosion rates is smaller in clay areas than peat areas since peat areas have higher organic content.

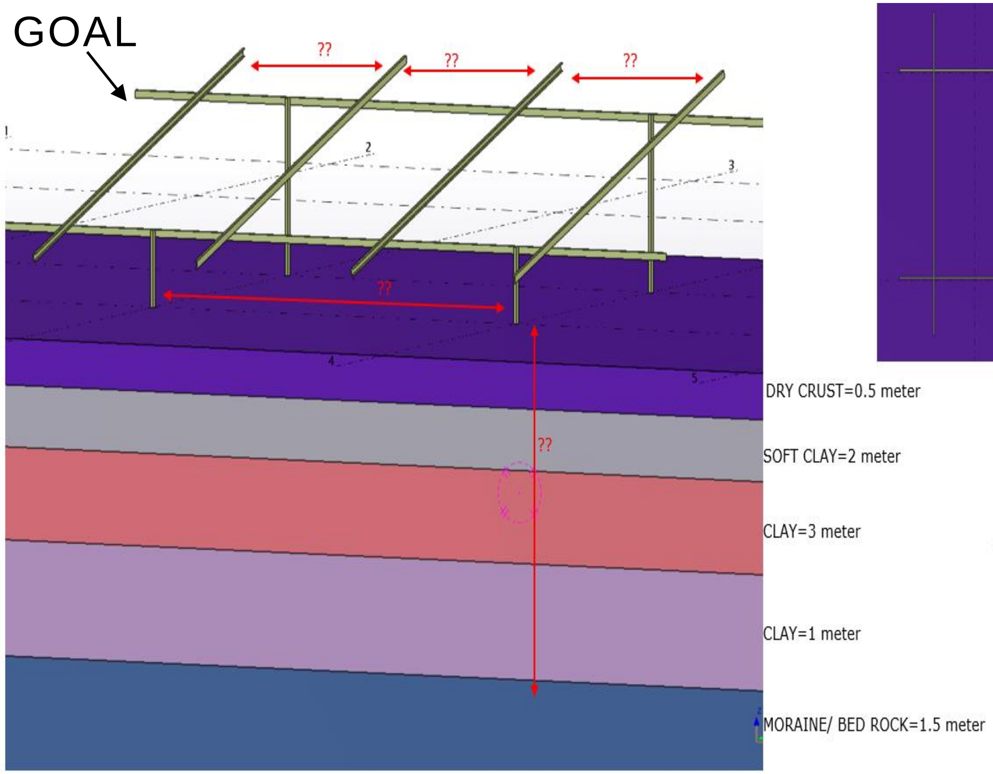
NCCI7 Appendix 5 Table 4 and 5 give guidance for unprotected steel above and below water table.

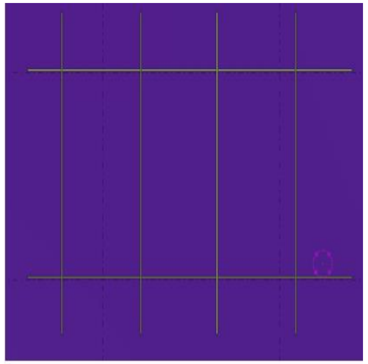
Taulukko 4. Korroosion aiheuttama seinämäpaksuuden menetys [mm] maassa oleville suojaamattomille teräspaaluille ja ponttiseinille pohjavedenpinnan ylä- ja alapuolella.

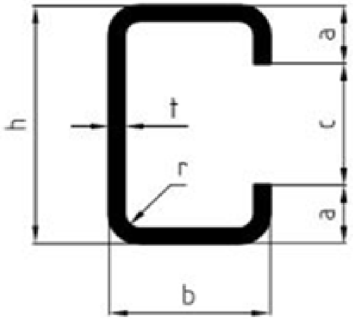
Suunniteltu käyttöikä	5 vuotta	50 vuotta	100 vuotta
Tavanomaiset olosuhteet			
Häiriintymättömät luonnonmaat (hiekka, siltti, savi, liuske)	0,00	1,00	2,00
Tiivistetyt, ei-aggressiiviset homogeeniset täyttömaat (sora, hiekka, siltti, savi) ja kiviaineksista tehdyt murskeet	0,10	1,00	2,00
Tiivistämättömät, ei-aggressiiviset homogeeniset täyttömaat (sora, hiekka, siltti, savi) ja kiviaineksista tehdyt murskeet	0,20	1,20	2,50
Tavanomaisesta poikkeavat tai aggressiiviset olosuhteet			
Saastuneet luonnonmaat ja teollisuusalueidenmaa-alueet	0,15	1,50	3,00
Aggressiiviset luonnonmaat (lieju, turve)	0,20	1,75	3,25
Tiivistämättömät ja aggressiiviset täyttömaat (tuhka, kuona)	0,50	3,25	5,75
Huom. Annetut arvot ovat minimiarvoja. Jos olosuhteet arvioidaan poikkeuksellisen aggressiiviseksi, niin taulukon 3 esittämät seinämäpaksuuden menetyksen suuruus ei ole riittävä, jolloin mitoitusperusteet on määritettävä tapauskohtaisesti.			

If the steel structures design life period is 50 year and the steel is inside the uncompacted clay soil with non-aggressive environment that will active the corrosion, then there might be loss of 1 mm of steel after 50 years. i.e 1 mm need to add in steel thickness in design phase.

STUDY CASE- FRAME OF SOLAR PANEL





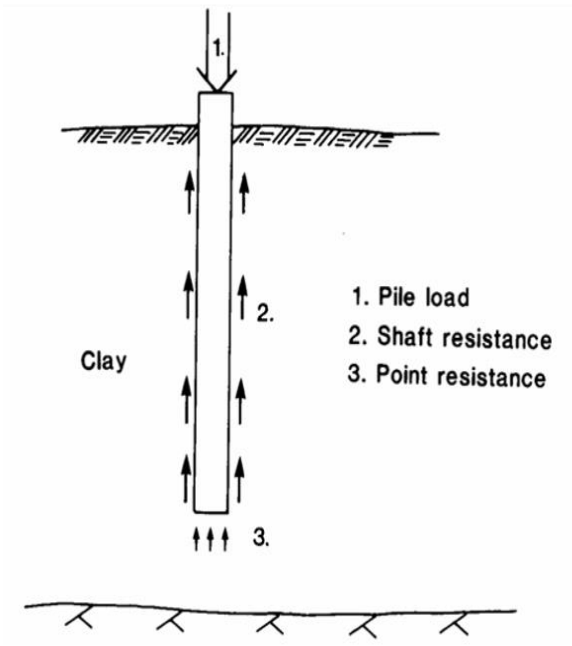


- Open Profile Steel pile embedded inside the soil. (i.e not inside rock only in soil layers.)
  - Ground condition 6-meter clay, about 1,5 meter of gravel moraine
- Not much guidance on such open structures like in Building or other infra structures.
  - Assume to be less impact on human life Structural Category Class 3.
  - Wind pressure in 21m/s
  - Normal Design life span 50 year for such structure.

Location of Solar Panel field.	Hakala
Water table	Assumbed to be at ground level
Structural Category Class	III
Design life span	50 years
Wind pressure	21 m/s

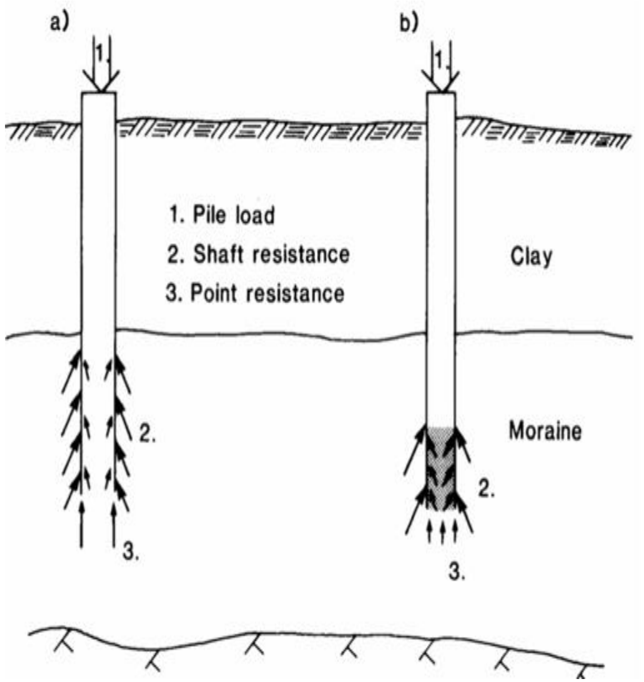
Typical Steel pile for solar panel

Cohesive Pile



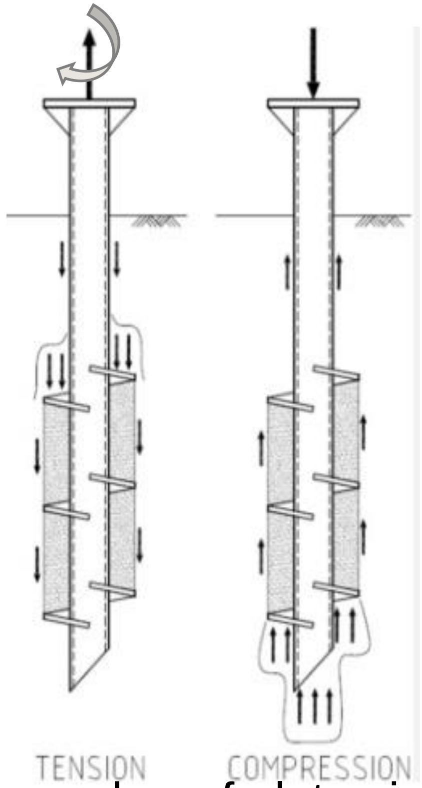
- load is supported through the shaft resistance and toe resistance.
- settlement in cohesive soil is higher.

Friction Pile



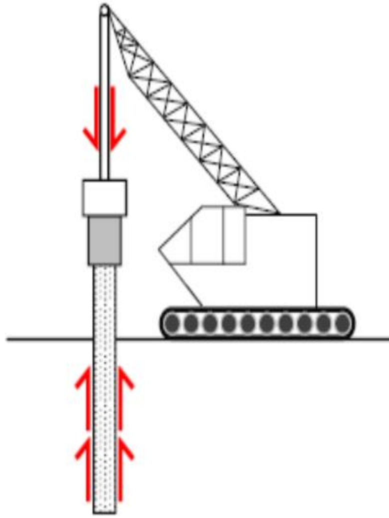
- skin of pile creates shear stresses which stand axial load.
- surrounding settles more than pile settlement **Negative Skin Friction.**

Helical Pile



- number of plates in the tip of helical piles significantly play major role in increasing the bearing capacity.
- Need rotational force in installation.
- High cost due to weld plate.

Driven Pile



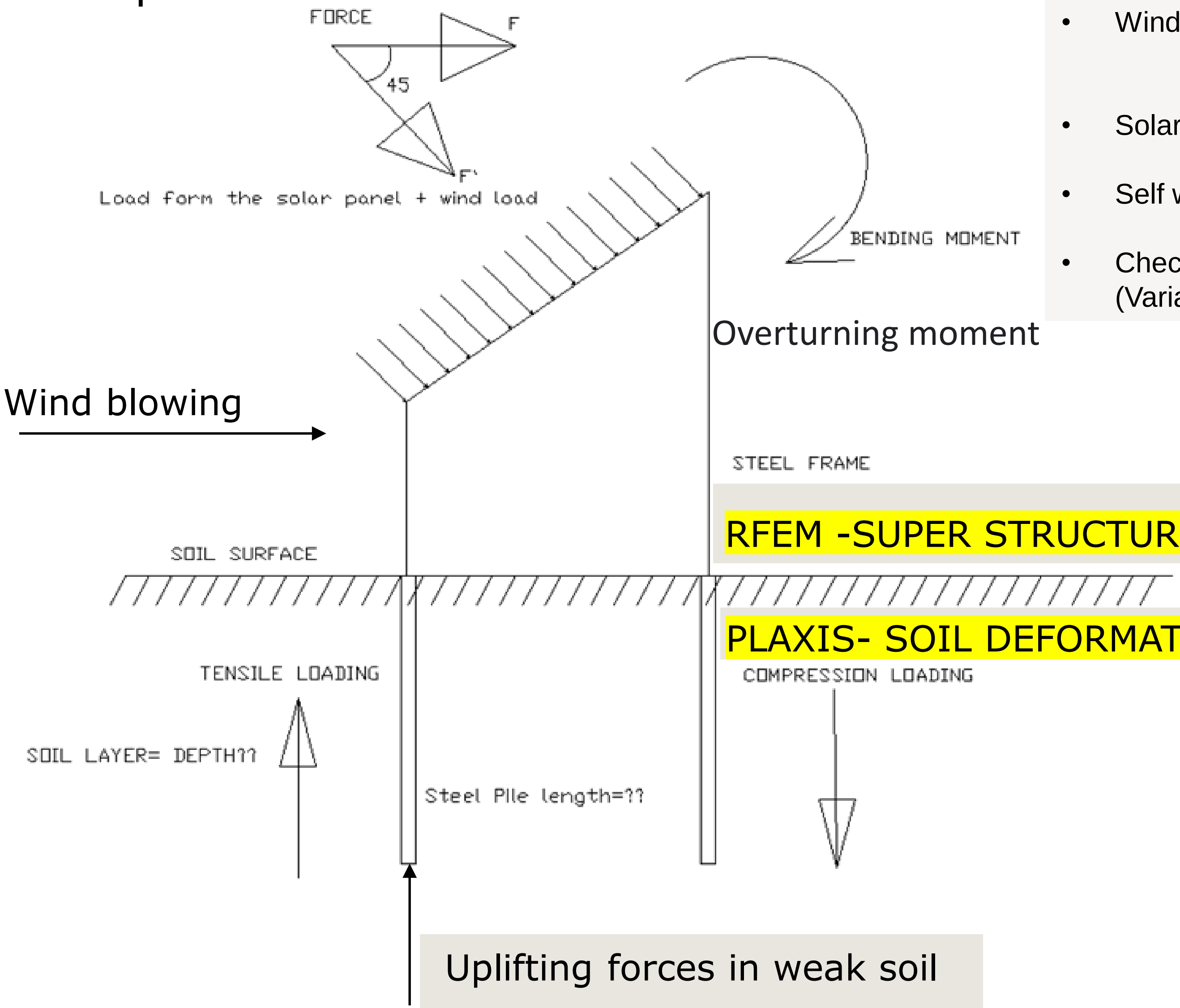
- Simple pile.
- Easy to install.
- Less cost.

Our Case focus only to small open cross section with cohesive and friction piles

STRUCTURAL ANALYSIS

LOAD	Magnitude
• Snow load (Variable) • Wind load (Variable)	• 2.5 kN/m2 • 21 m/s (Class 3) low building high vegetation
• Solar Panel own weight (Permanent)	• 0.278 kN/m2 (One of Finnish Solar Panel Manufacturer)
• Self weight of Steel	• 5 kg/m > 0,05 kN/m (One of SSAB Product 100/50x3 profile)
• Check if there is Cyclic Loading (Variable)	• Load (kN)/ Time(s)

Example Case



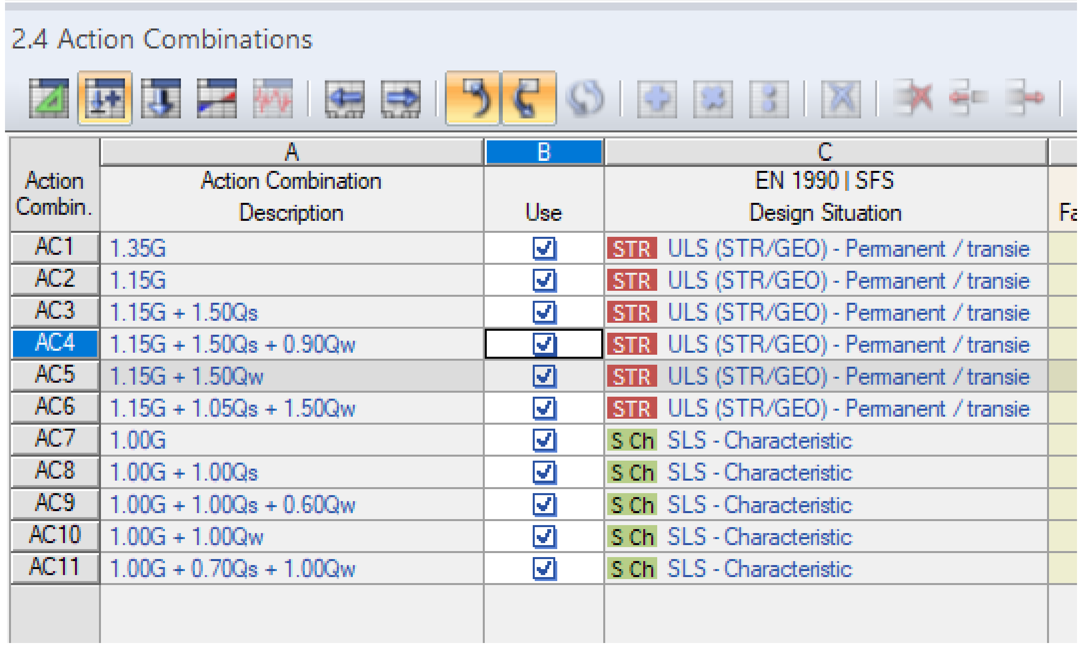
Wind blowing

Overturning moment

RFEM -SUPER STRUCTURE

PLAXIS- SOIL DEFORMATION

Uplifting forces in weak soil

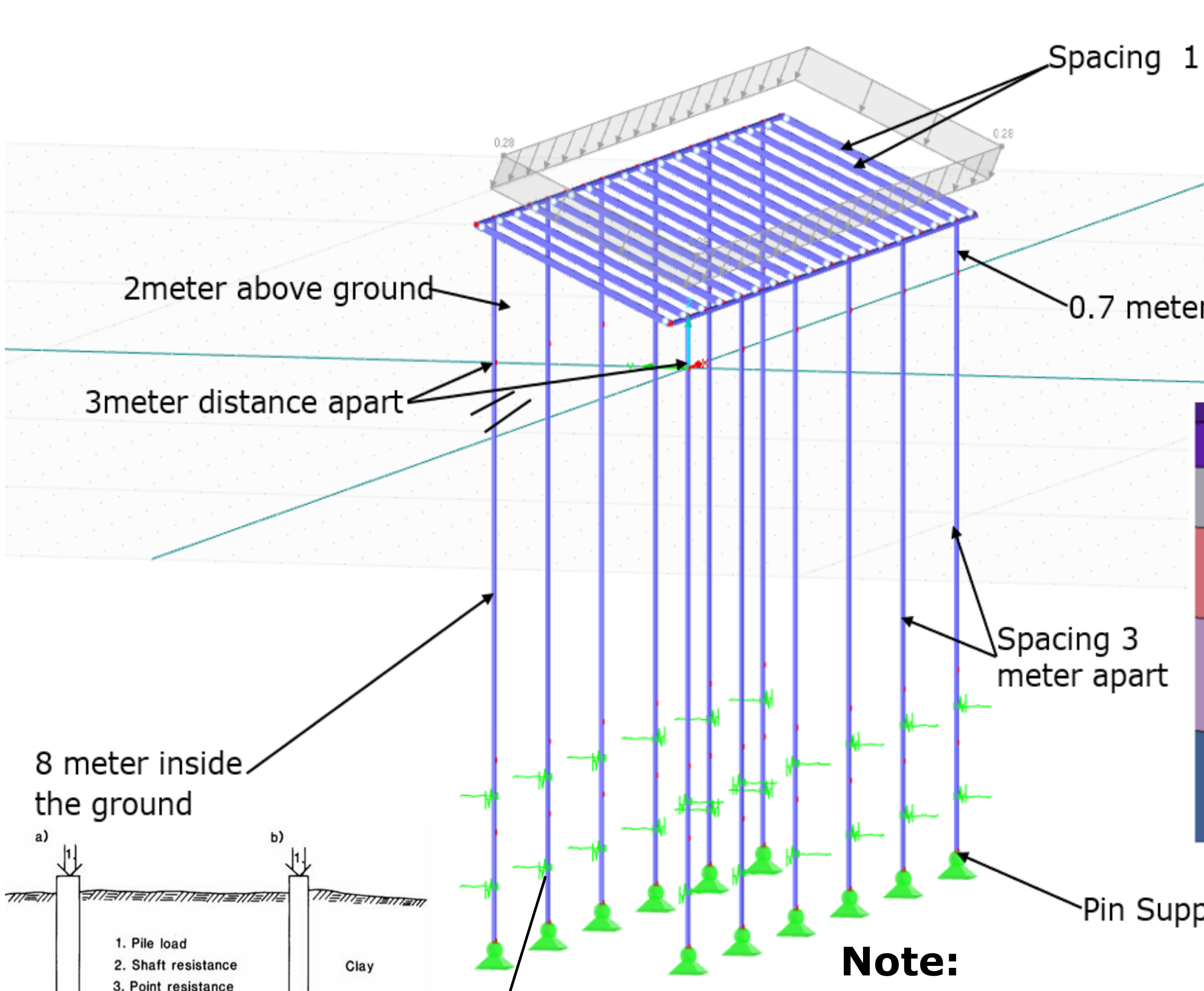


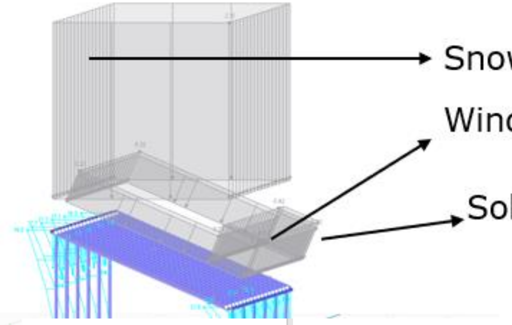
2.4 Action Combinations

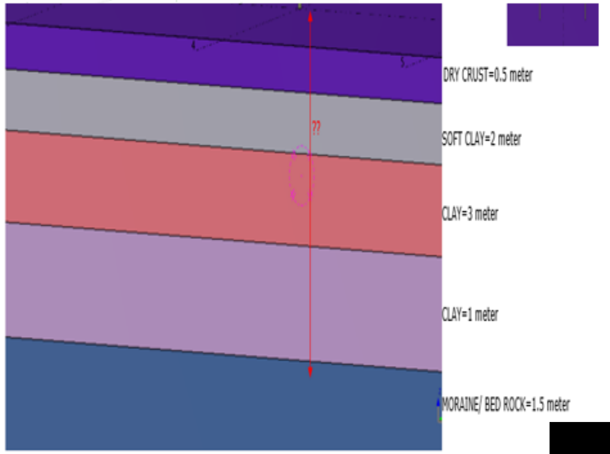
Action Combin.	A Action Combination Description	B Use	C EN 1990 | SFS Design Situation	Fa
AC1	1.35G	☑	STR ULS (STR/GEO) - Permanent / transie	
AC2	1.15G	☑	STR ULS (STR/GEO) - Permanent / transie	
AC3	1.15G + 1.50Qs	☑	STR ULS (STR/GEO) - Permanent / transie	
AC4	1.15G + 1.50Qs + 0.90Qw	☑	STR ULS (STR/GEO) - Permanent / transie	
AC5	1.15G + 1.50Qw	☑	STR ULS (STR/GEO) - Permanent / transie	
AC6	1.15G + 1.05Qs + 1.50Qw	☑	STR ULS (STR/GEO) - Permanent / transie	
AC7	1.00G	☑	S Ch SLS - Characteristic	
AC8	1.00G + 1.00Qs	☑	S Ch SLS - Characteristic	
AC9	1.00G + 1.00Qs + 0.60Qw	☑	S Ch SLS - Characteristic	
AC10	1.00G + 1.00Qw	☑	S Ch SLS - Characteristic	
AC11	1.00G + 0.70Qs + 1.00Qw	☑	S Ch SLS - Characteristic	

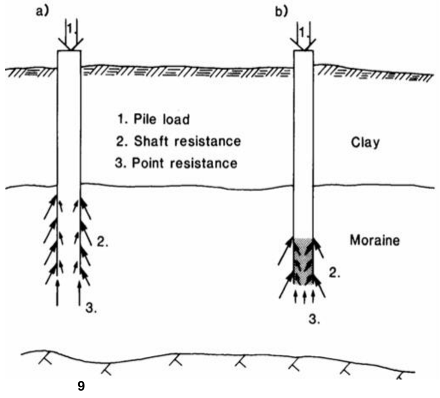
Different Load cases are studied with combination factor under ULS state.

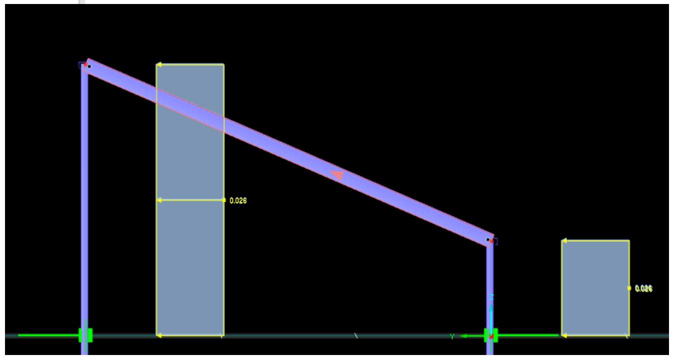
ANALYSING EXAMPLE CASE IN RFEM- FRICTION PILE – 3 METERS SPACINGS.









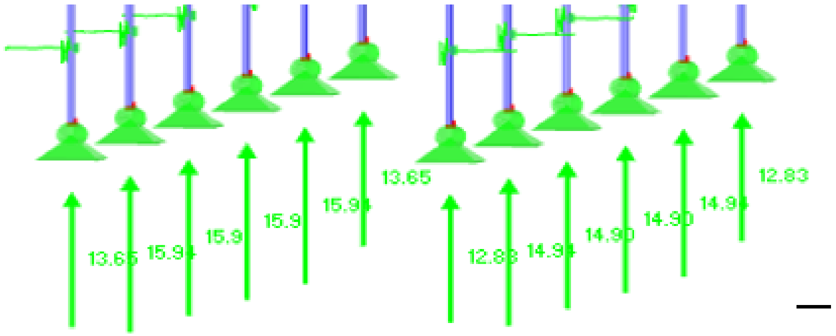


Note:

<u>In the first stage the length was assumed to be 8 meter long in the soil. Later Optimization will be done in analysis phase.</u>

UPLIFTING & CYCLIC LOADING

- Horizontal wind load causing the Overturning moments in the structure.
- Piles can resist the uplifting forces through the frictional forces between the pile and soil inside ground.
- On one load combination the uplifting forces for the piles were max**16 kN**.



Load case when all the forces are acting all same time

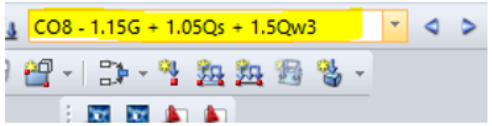
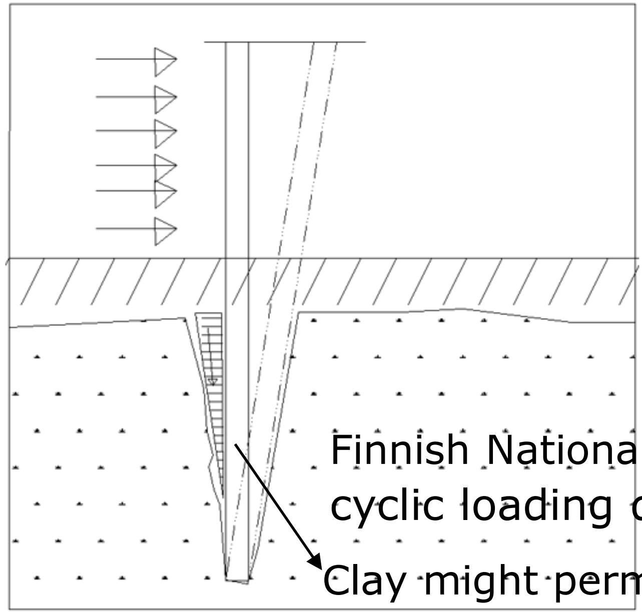


Table 5. The lateral subgrade reaction of the cohesionless soil k_{ss} for cyclic loading /8/. k_s = static subgrade reaction

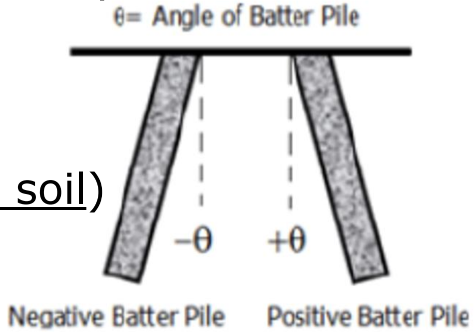
Subgrade reaction for cyclic loading	Relative density D_r		
	< 0,35 Loose	0,35...0,65 Medium dense	> 0,65 Dense
k_{ss}	0,25 k_s	0,33 k_s	0,5 k_s

— In Site visit it was found that 20 kN force was needed to uplift the pile which was 2 meter inside the Clay.



- Cyclic loads are generated due to several wave of wind per hour to structures.
- Cyclic failure in Noise barrier high velocity of air over time, barrier of rail track train movement.'

- Many research suggests negative batter angular micro pile increase resistance toward static and cyclic loading.



Finnish National road Administration (FinnRA) Bridge Steel pile cyclic loading determined table 5 in paragraph 4.9.7. (<u>Cohesionless soil</u>)

Clay might permanent deformation due to several wave cycle of wind.

Calculation of Spring constant in soft soil

NCCI7 Annex 9

Paalujouset

Pile springs for cohesion soil — **Clay 1 meter on bottom**

Shear strength of soil	C_u	10	kN/m²		
Spring spacing	L_{jousi}	1,00	m		

Pile	D	Short term		Long term	
		k_s	k_j	k_s	k_j
	[m]	[kN/m³]	[kN/m]	[kN/m³]	[kN/m]
C 100/50x4 (b=50)	0,05	30000	1500	10000	500
			30000		
			kN/m²		

Pile deformations

	Short term	Long term		
P_m	90	60	kN/m²	side pressure of the pile
$y_{m,epälin.}$	9	15	mm	non-linear deformation of the pile
$y_{m,lin.}$	1,5	3	mm	linear deformation of the pile (characteristic deformations under horizontal load of the pile cannot exceed this value in the model if linear theory is used)

Paalujen siirtymä jarrukuormasta

$y_{m,jarru}$ 4,106 mm taken from the model

Ehto

$y_{m,jarru}$	≤	$y_{m,lin.}$		
4,11	≤	1,5	KA	274 %

Pile spirings for friction soil — **Moraine Layer 1,5 meter on bottom**

Pile springs above ground water level?

Kyllä

ϕ_s	36	°	friction angle of the soil
n_h	4,75	MN/m³	spring coefficient factor of friction soil
z	1	m	depth of the spring from the ground
d	0,1	m	diameter or side length of thepile
k_s	47500	kN/m³	
k_j	4750	kN/m	kj= 47500 kN/m²

Kitkakulman alustalukukerroin

ϕ_s	30	31	32	33	34	35	36	38	40	42,5	45		47,5	50
n_h	0,01	1	1,45	2,4	3	4	4,75	8,3	12	18,5	26,5		35	45
							4,75	4,6	1,6	-2,3			-11	
							4,75							

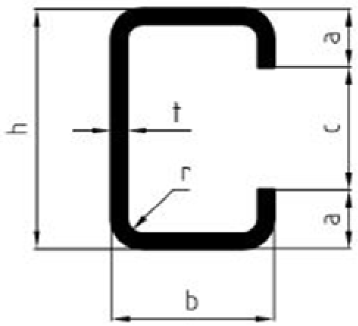
when d=0,1

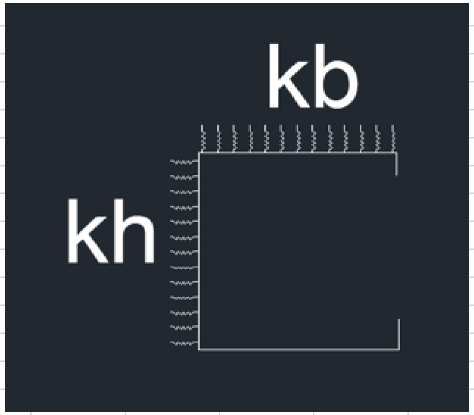
	C-Profile	mm
	h=	100
	b=	50

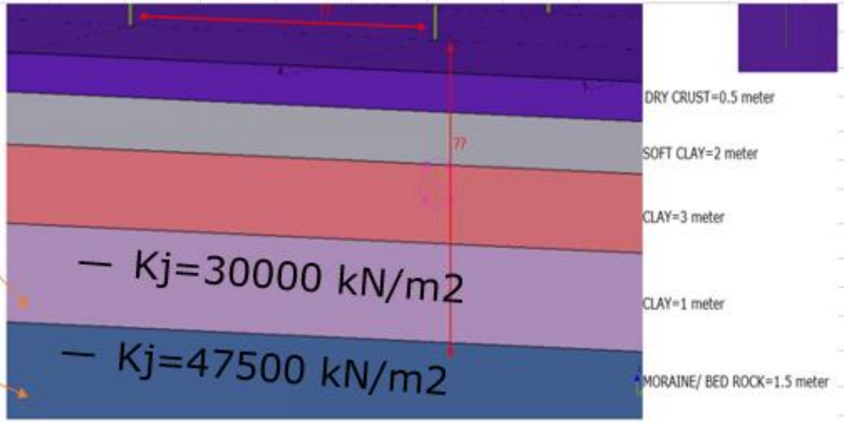
Value of spring contant in direction of h kh

Value of spring contant in direction of b kb

C-profile







Paalujouset PVP:n yläpuolella?

Kyllä

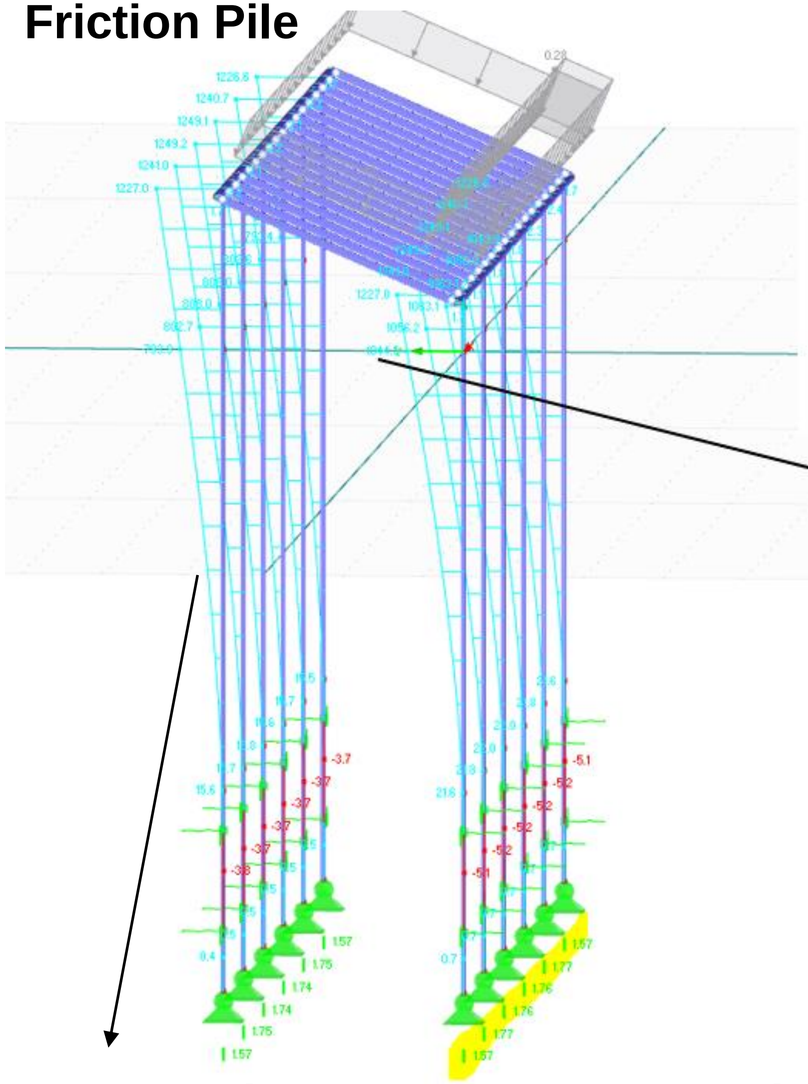
Ei

Valitut paalut

Paalu	D	
	[m]	
RTC-300-16	0,3	
C 100/50x4 (h=100)	0,1	side length (in direction of b=100)
C 100/50x4 (b=50)	0,05	side length (in direction of b=50)

CHECKING DEFORMATION UNDER ULS WITHOUT USING SPRING SUPPORT FROM CLAY

Friction Pile



A.6.1 General

(1) A specimen under test should be regarded as having failed if the applied test loads reach their maximum values, or if the gross deformations exceed specified limits.

(2) The gross deformations of members should generally satisfy:

$$\delta \leq L/50 \quad \text{... (A.6)}$$

$$\phi \leq 1/50 \quad \text{... (A.7)}$$

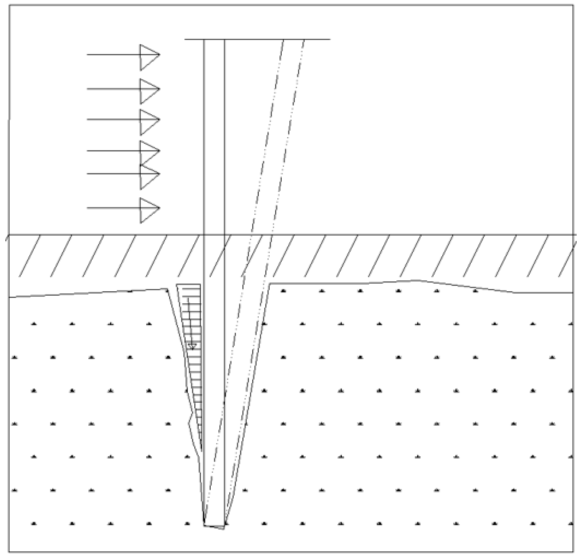
where:

δ is the maximum deflection of a beam of span L;

ϕ is the sway angle of a structure.

- Deformation 1063 mm
- Smallest deformation accoring to eurocode is L/50 (8000/50=160mm)
- (Length of pile L =8000 meter)
- Uplfiting force 1.57 kN

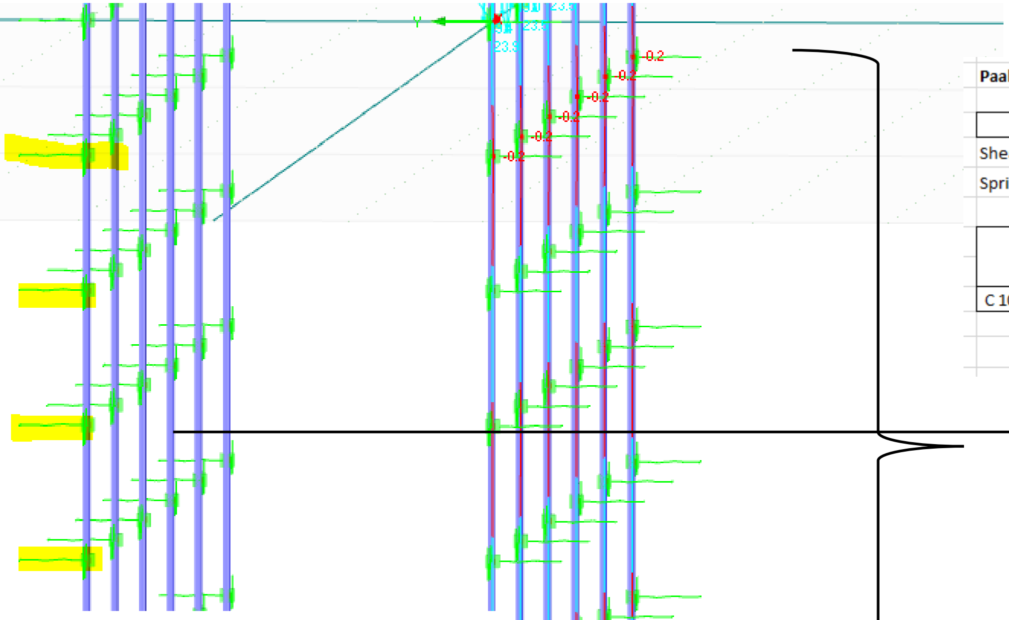
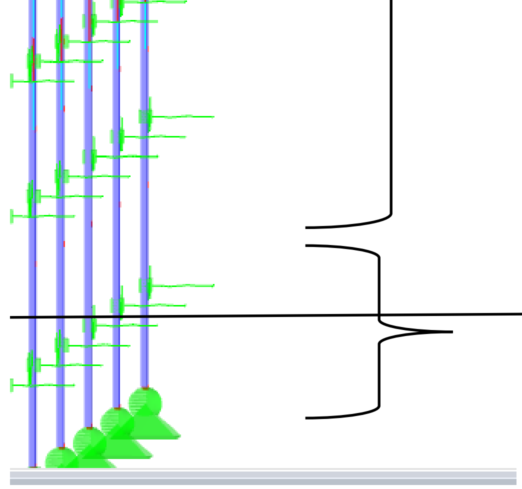
—VERY HIGH DEFORMATION!!!



No soil support at top assuming it might be because to cyclic loading.

ASSUMPTION 1

When spring support is at 1 meter intervals in the soil.

Paalujouset

Pile springs for cohesion soil						
Shear strength of soil	C_u		10	kN/m²		
Spring spacing	L_{jousi}		1,00	m		
		Short term		Long term		
Pile	D	k_s	k_j	k_s	k_j	
	[m]	[kN/m³]	[kN/m]	[kN/m³]	[kN/m]	
C 100/50x4 (h=100)	0,1	15000	1500	5000	500	
			15000			
			kN/m²			

- Calculated spring constant value in direction of h =15000 kN/m2

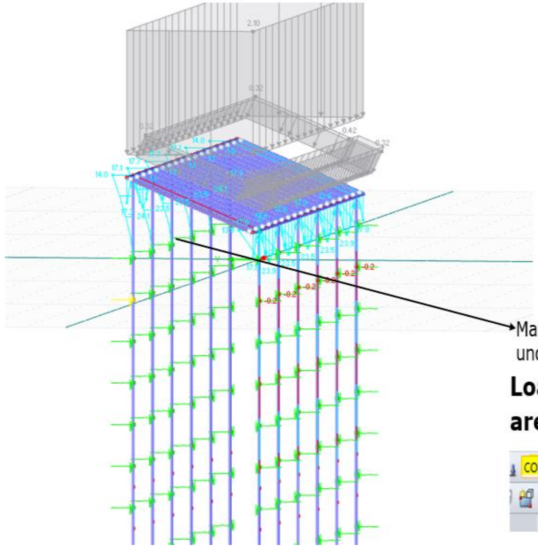
Clay layer

Paalujouset

Pile springs for cohesion soil						
Shear strength of soil	C_u		10	kN/m²		
Spring spacing	L_{jousi}		1,00	m		
		Short term		Long term		
Pile	D	k_s	k_j	k_s	k_j	
	[m]	[kN/m³]	[kN/m]	[kN/m³]	[kN/m]	
C 100/50x4 (b=50)	0,05	30000	1500	10000	500	
			30000			
			kN/m²			

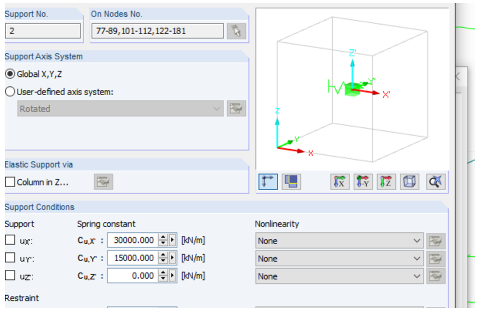
- Calculated spring constant value in direction of b =30000 kN/m2

Moraine Layer

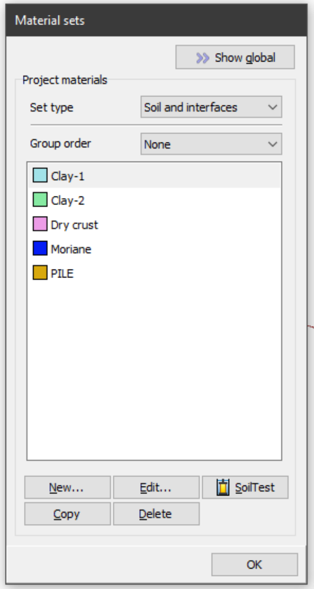


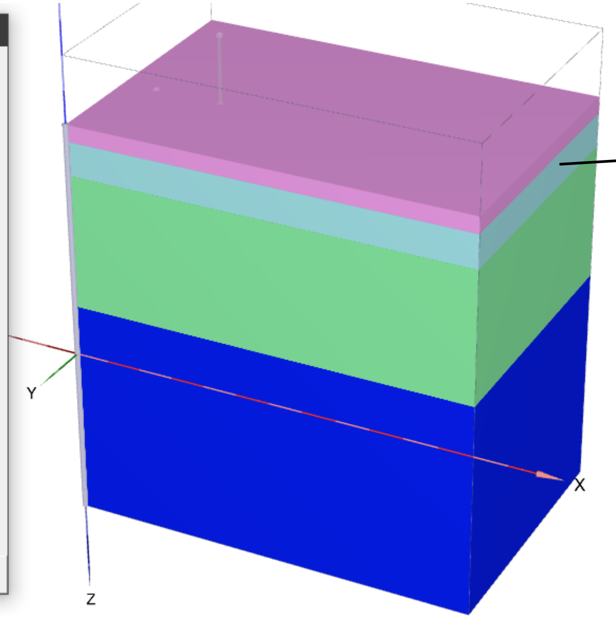
MaxDeformation = about 17 mm max which is under 160 mm

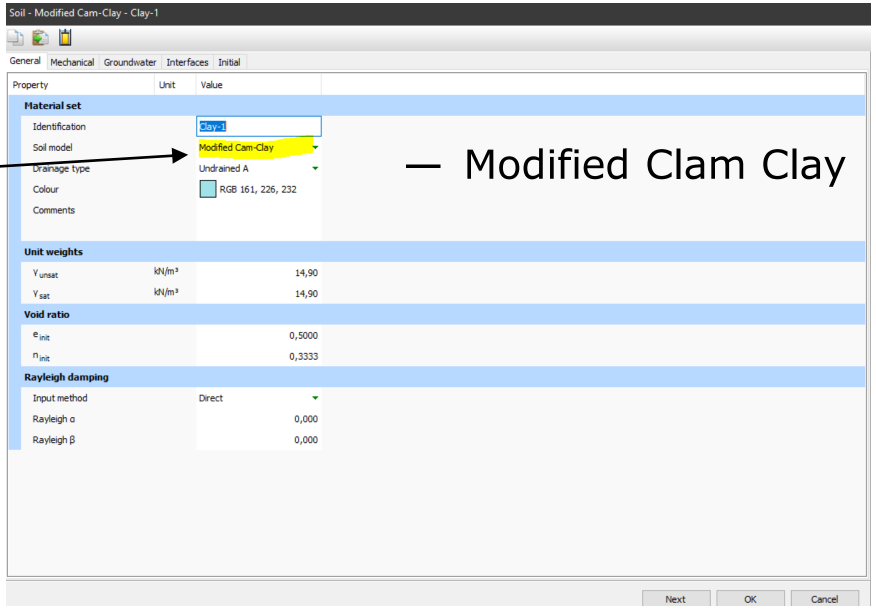
Load case when all the forces are acting all same time



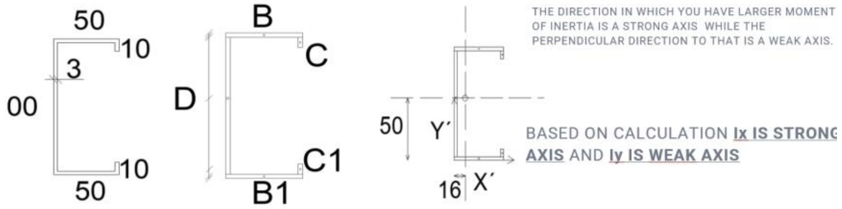
To check the spring constant values and obtain same deformation. PLAXIS 3D model is created for single pile under same load.







— Modified Clam Clay

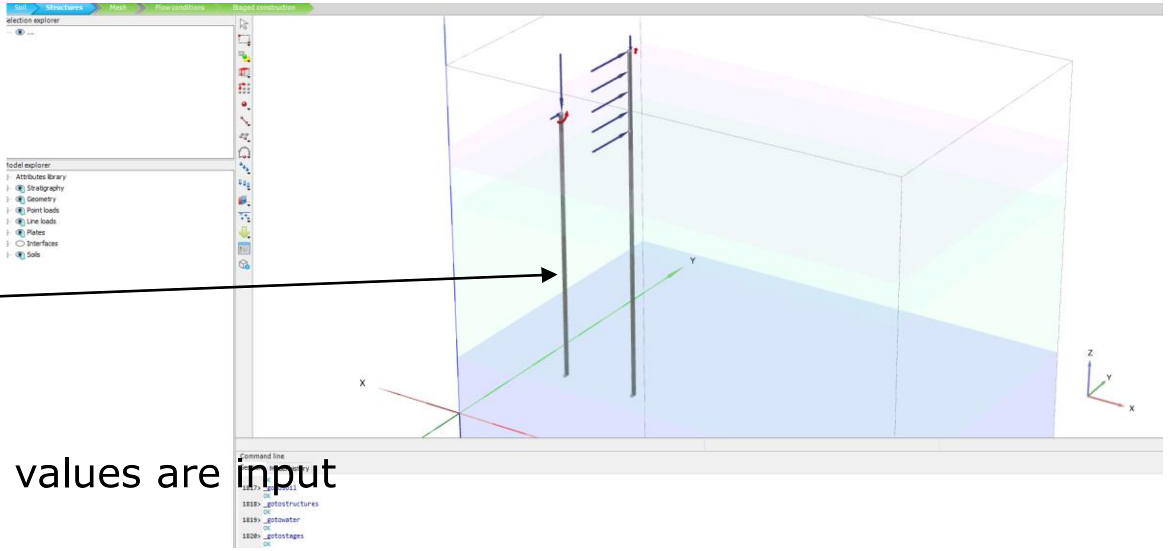


Moment of Inertia About XX axis **(Ixx)** and Moment of Inertia about YY axis **(Iyy)**

t=3 mm

	Area A (mm2)	Y-axis (distance from bottom to centeroid) mm	A*Y (mm3)	X-axis (distance from bottom to centeroid) mm	A*X (mm3)	IGx= (bd³/12)mm⁴	Ah² (mm⁴)	Ixx= IGx + Ah² mm⁴	IGy= (bd³/12) mm⁴	Ah² (mm⁴)	Iyy= IGy + Ah² mm⁴
A	282	50	14100	1,5	423	207646	0	207646	211,5	58976,38	59187,88
B1	150	1,50	225	25	3750	112,5	352837,5	352950	156250	12254,07	168504,1
C1	21	6,5	136,5	48,5	1018,5	85,75	39737,25	39823	15,75	22233,78	22249,53
B	150	98,5	14775	25	3750	112,5	352837,5	352950	156250	12254,07	168504,1
C	21	93,5	1963,5	48,5	1018,5	85,75	39737,25	39823	15,75	22233,78	22249,53
Sum	624	250	31200	148,5	9960			**993192**			**440695**

Centroid of Composite structure		
Y´=∑(A*Y/A)	50	mm
X´=∑(A*Y/A)	15,96	mm



— Pile is created as layer and Moment values are input

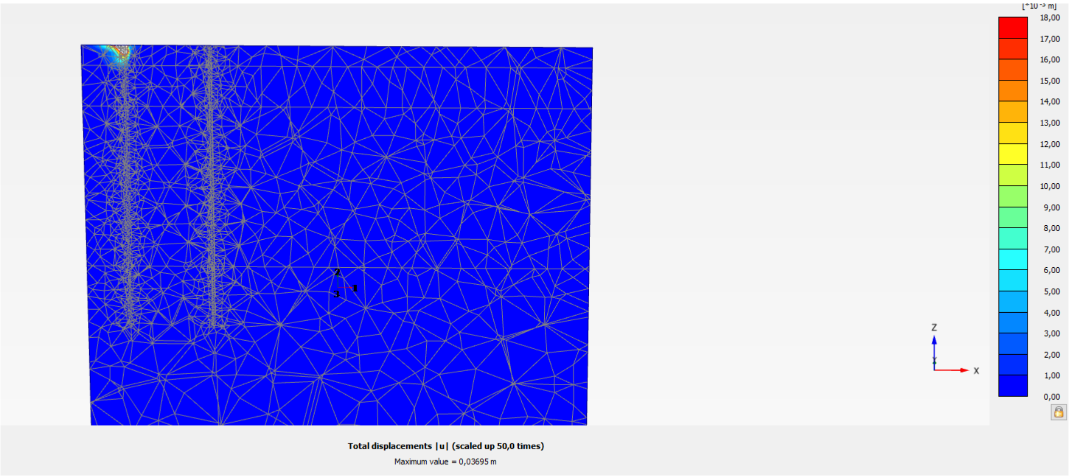
Modified Clam Clay Parameters.

FIELD TEST RESULT AT DIFFERENT PARTS OF FINLAND.

Table 5. Values for the parameters and intitial state variables used in the simulations.

Model	λ	κ	ν'	M	μ	β	α_0	p'_{m0} (kPa)
Murro clay								
MCC	0.21	0.034	0.30	1.60	—	—	—	44.5
S-CLAY1	0.21	0.034	0.30	1.60	20	1.02	0.46	35.5
Otaniemi clay								
MCC	0.26	0.040	0.25	1.30	—	—	—	33.0
S-CLAY1	0.26	0.040	0.25	1.30	20	0.86	0.42	26.0
Vanttila clay								
MCC	0.30	0.057	0.20	1.35	—	—	—	32.3
S-CLAY1	0.30	0.057	0.20	1.35	15	0.91	0.40	26.0

(M. Koskinen 2014)

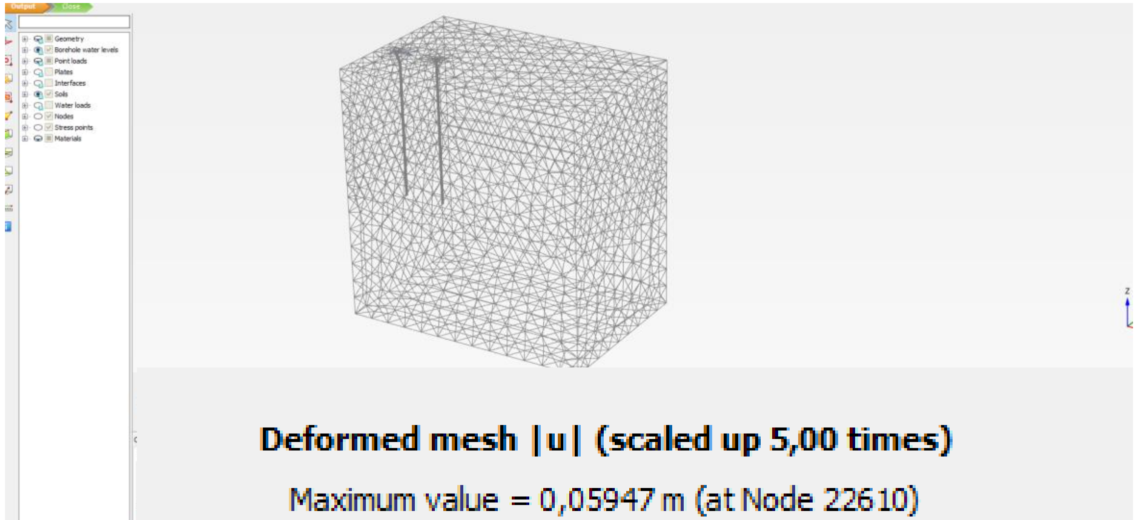


Thus the test in Plaxis is valid only if the clay properties is with in the following range.

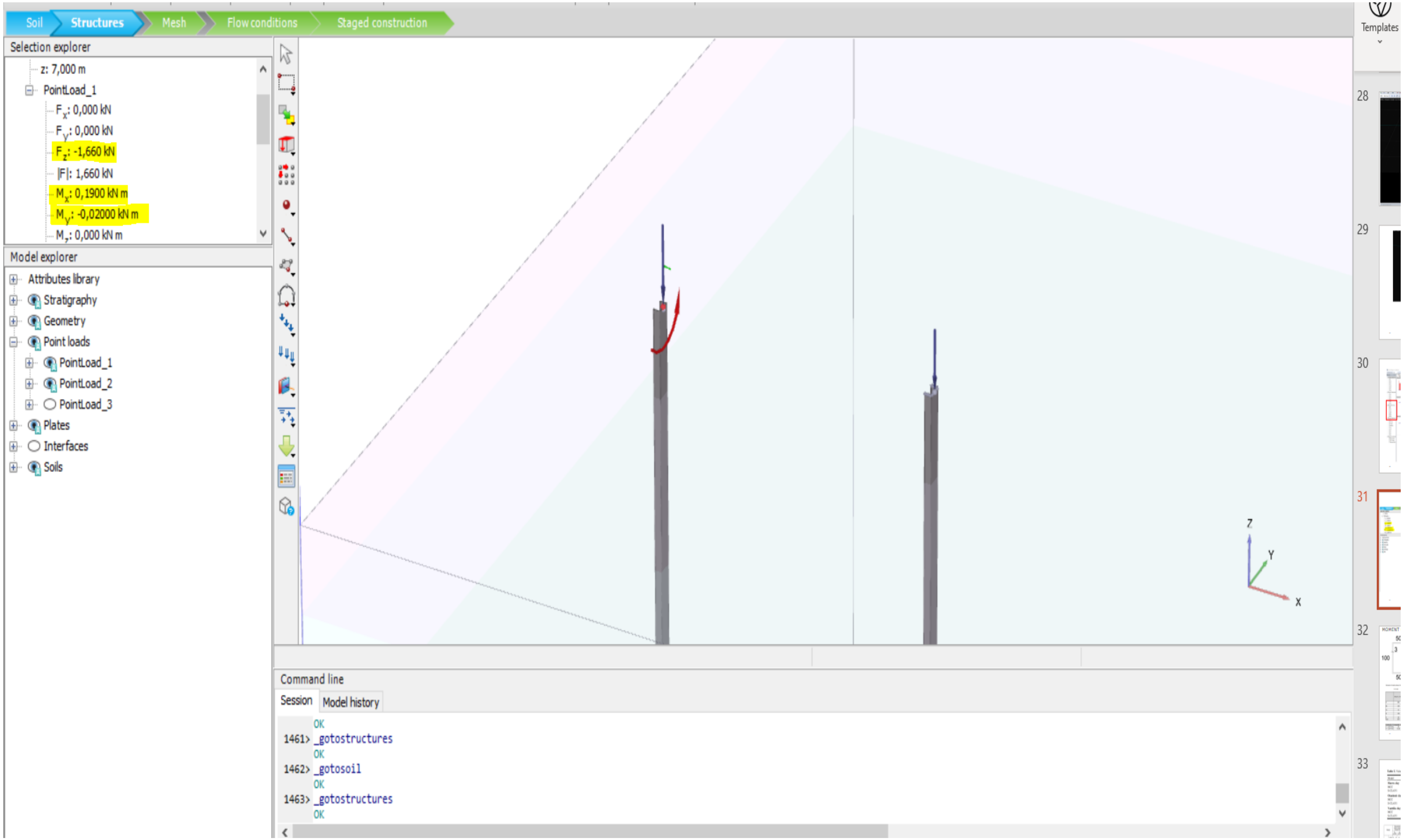
Clay Propetise	λ	κ	v´	M	μ	β	α_o	p'_{m0} (kpa)
MCC	0.21-0.30	0.034-0.057	0.20-0.30	1.30-1.60	-	-	-	32-44
S-CLAY 1	0.21-0.30	0.034-0.057	0.20-0.30	1.30-1.60	15-20	0.86-1.02	0.40-0,46	26-35

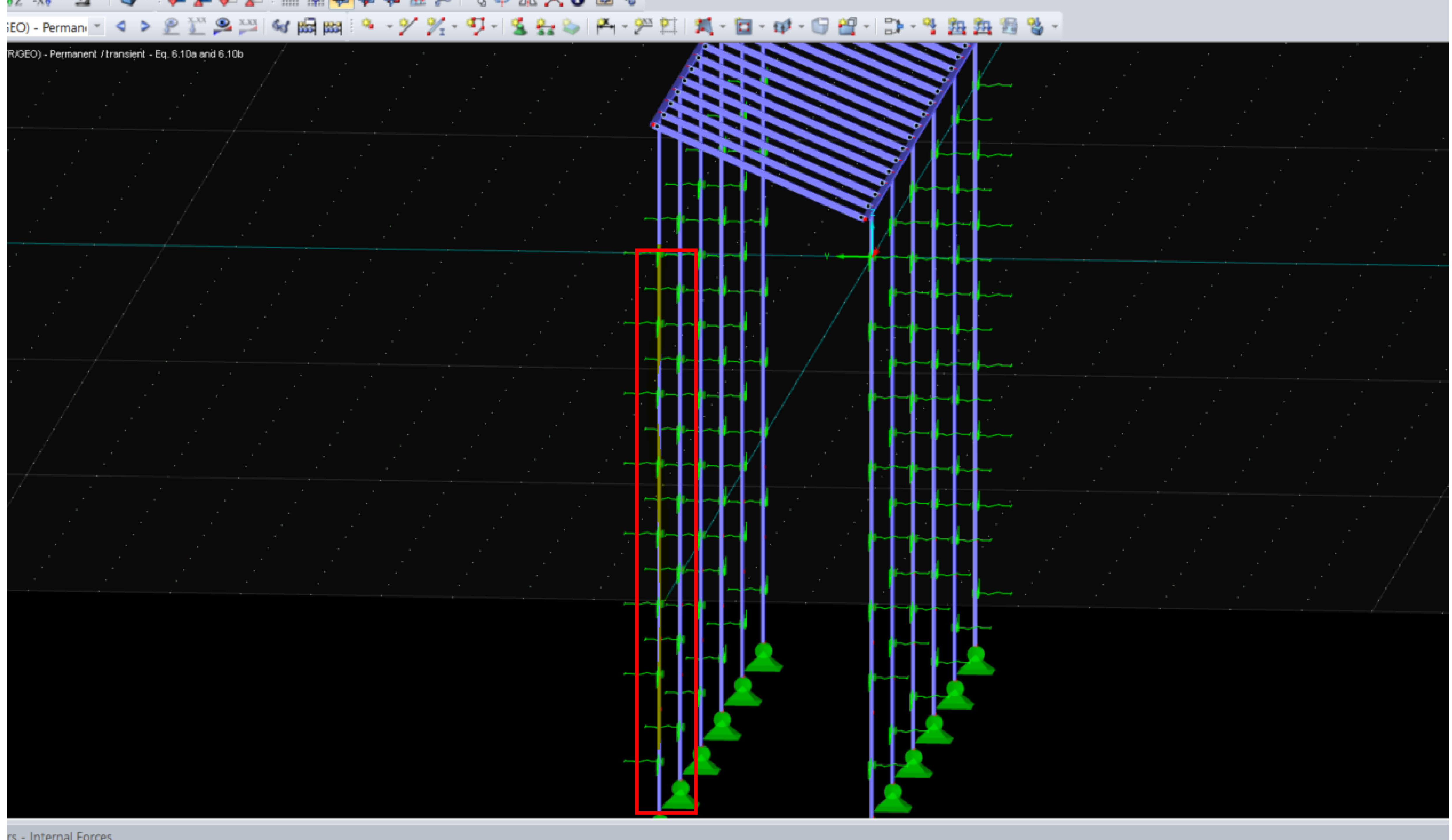
The taken value of Clay properties in the Plaxis 3D analysis for the research is shown in the following table which is chosen from the above range.

Clay Propetise	λ	κ	v´	M	μ	β	α_o	p'_{m0} (kpa)
MCC	0.26	0.040	0.25	1.30	-	-	-	33
S-CLAY 1	0.26	0.040	0.25	1.30	20	0.86	0.42	26

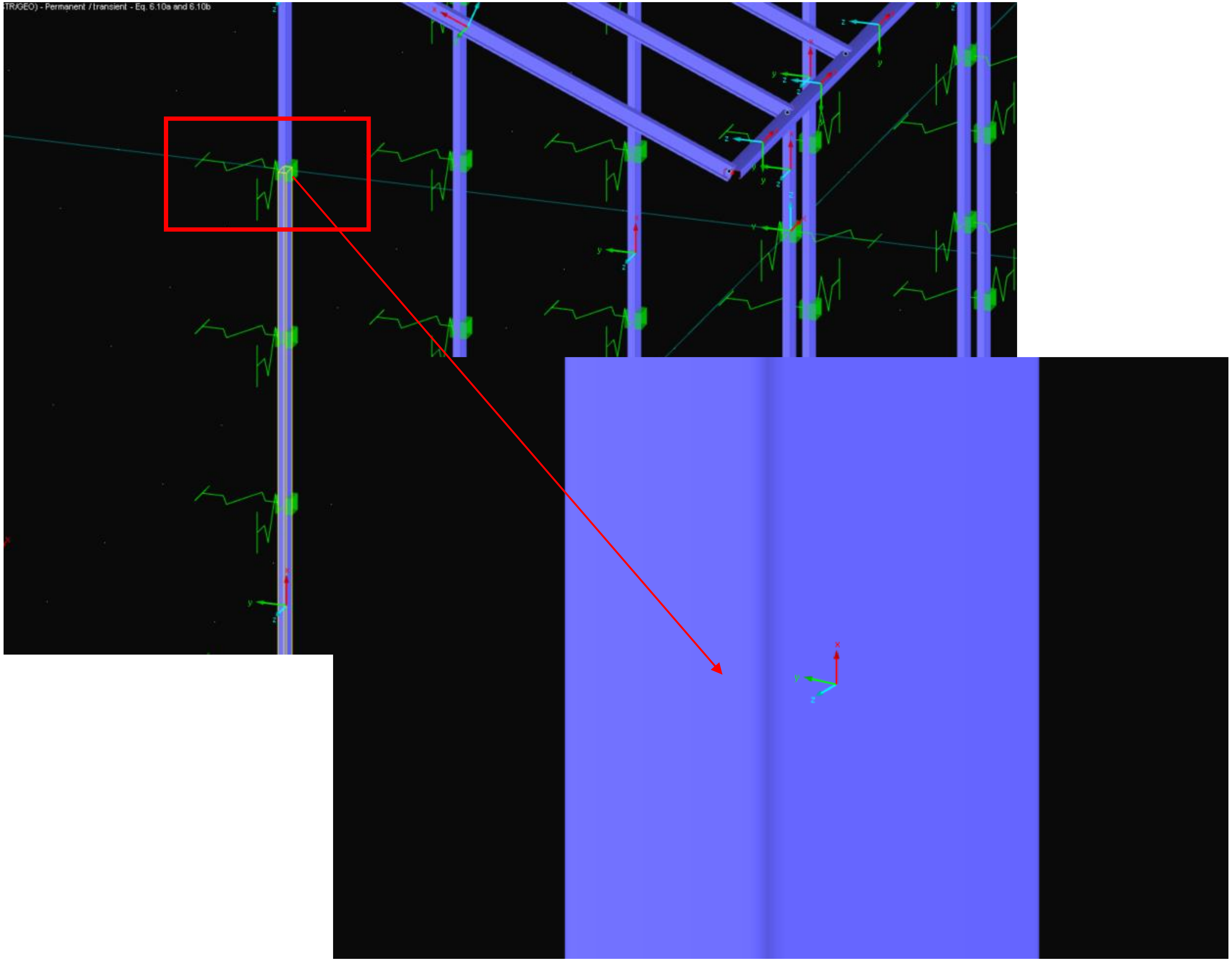


Deformation 59 mm

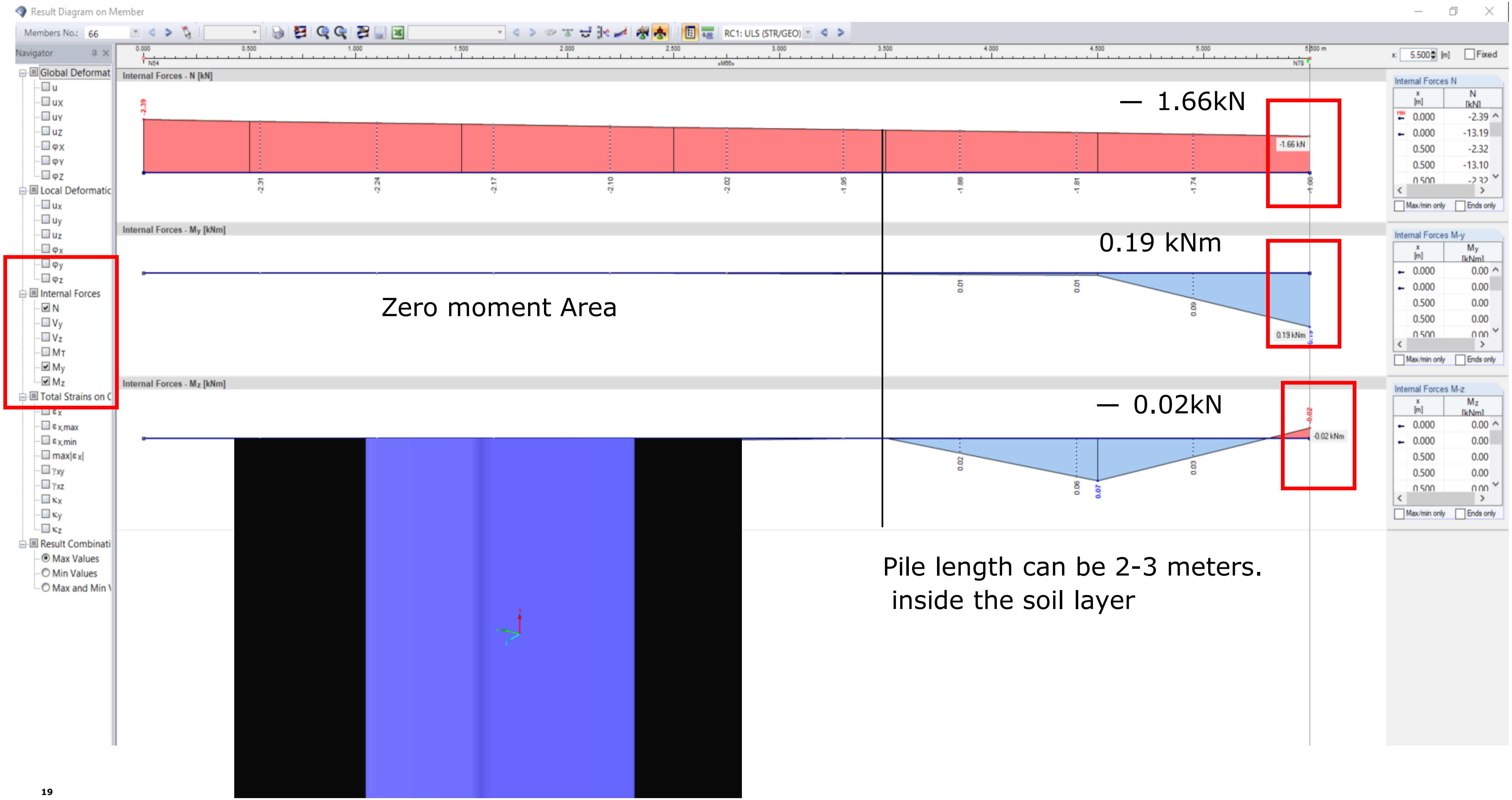

Soil
Structures
Mesh
Flow conditions
Staged construction
Templates
Selection explorer
z: 7,000 m
PointLoad_1
F$_x$: 0,000 kN
F$_y$: 0,000 kN
F$_z$: -1,660 kN
|F|: 1,660 kN
M$_x$: 0,1900 kN m
M$_y$: -0,02000 kN m
M$_z$: 0,000 kN m
Model explorer
Attributes library
Stratigraphy
Geometry
Point loads
PointLoad_1
PointLoad_2
PointLoad_3
Plates
Interfaces
Soils
Z
Y
X
Command line
Session
Model history
OK
1461> _gotostructures
OK
1462> _gotosoil
OK
1463> _gotostructures
OK
28
29
30
31
32
33



EO) - Perman
R/GEO) - Permanent / transient - Eq. 6.10a and 6.10b
rs - Internal Forces


STR/GEO) - Permanent / Transient - Eq. 6.10a and 6.10b

— Bending moment about both axis, Internal force, Shear force Single Pile



Pile length can be 2-3 meters.
inside the soil layer

Further Steps:
Optimization of Steel Pile

Method 1:
-Decreasing Pile length 3 meter inside soil.
-Spacing of pile 3-meters apart to 4-meters.

↓

Checking Deformation

↓

Calculating/Checking Shaft resistance to Cohesive Pile -NCCI7

↓

Checking Buckling

↓

Checking Uplifting

↓

Reduction/optimization of pile lengths in soil

CALCUALTION OF SHAFT RESISTANCE
1.COHESIVE PILE

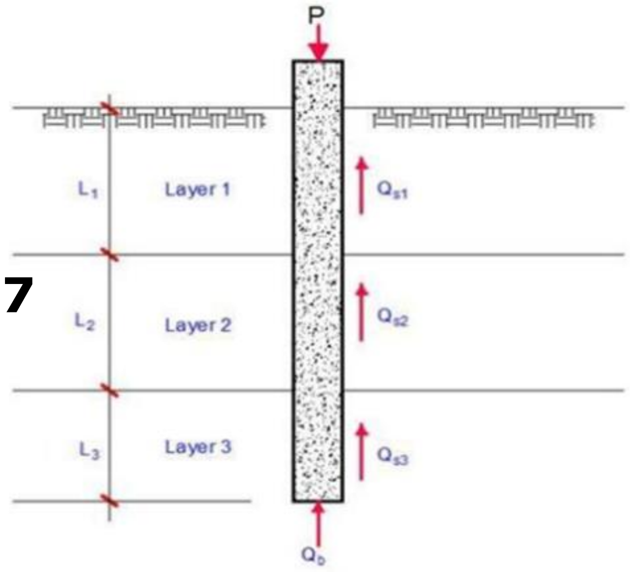


***Figure 4**: Pile in a layered soil*

Hence ultimate pile resistance Q_u;

$Q_u = \Sigma Q_s + Q_b$ —— (1)

Q_s = Shaft resistance = $q_s A_s$
Q_b = Base resistance = $q_b A_b$

Thank You